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(54) Title: ELECTROSURGICAL GENERATOR AND SYSTEM FOR UNDERWATER OPERATION

(57) Abstract

A radio frequency generator for an electrosurgical system is provided, the system including an electrode assembly having two electrodes for use immersed in an electrically conductive fluid. The generator has control circuitry for rapidly reducing the delivered radio frequency output power by at least 50 % within at most a few cycles of the peak radio frequency output voltage reaching a predetermined threshold limit. In this way, tissue coagulation can be performed in, for example, saline without significant steam generation. The same peak voltage limitation technique is used in a tissue vaporisation or cutting mode to limit the size of the steam pocket at the electrodes and to avoid electrode burning. The generator has a push–pull output stage with a series–resonant output circuit, the output stage being driven by a radio frequency oscillator at a frequency which, in general, differs from the resonant frequency of the resonant output circuit. Power control is achieved by varying the ON–time of switching transistors forming the push–pull output pair and by altering the frequency spacing between the excitation frequency and the resonant frequency of the series–resonant output circuit. In an alternative embodiment, a bridge configuration using two push–pull pairs is used, yielding a further power control variable: the relative phase of the driving signals to the respective transistor pairs.

ELECTROSURGICAL GENERATOR AND SYSTEM FOR UNDERWATER OPERATION

This invention relates to an electrosurgical generator for delivering electrosurgical energy particularly but not exclusively in so-called underwater electrosurgery. The invention also relates to an electrosurgical system comprising the combination of a generator and an electrode assembly.

The term "underwater electrosurgery" is used in this specification to denote surgery performed using an electrosurgical instrument with a treatment electrode or electrodes immersed in liquid at the operation site, generally liquid introduced to distend a body cavity containing the operation site or to wash blood away from the site. Alternatively, surgery may be performed with the electrode or electrodes immersed in naturally occurring body fluids. The invention has particular application in the fields of urology, hysteroscopy and arthroscopy. It should be understood, however, that the invention includes features which may have application also in electrosurgery not involving electrode immersion.

The background to underwater electrosurgery and intracavitary surgery, i.e. surgery in which living tissue is treated by least invasive surgical access to a body cavity, is described in our co-pending European Patent Application No. 96304558.8 (0754437), the contents of which are incorporated in this specification by reference.

Effective electrosurgical treatment of tissue which is totally immersed in liquid at the application site is difficult to achieve because the heat generated by the flow of electrical currents in both the tissue being treated and surrounding conductive liquid tends to cause boiling of the liquid. The operating electrode is intermittently surrounded by water vapour rather than liquid, with consequent large variations in the electrical impedance of the load presented to the generator supplying the electrosurgical power to the electrode. Whilst this variation is mitigated by use of a non-conductive liquid, it cannot be eliminated entirely due to the release of body fluids at the operative site which elevates the electrical conductance of the liquid. Changes in

tissue type also alter the load impedance. These effects result in difficulty in controlling the electrosurgical output to produce consistent effects on the tissue being treated. As a result, high powers are commonly employed to overcome this performance variation.

5   According to a first aspect of this invention, an electrosurgical generator for supplying radio frequency power to an electrical instrument comprises a radio frequency output stage having at least a pair of electrosurgical output lines for the delivery of radio frequency power to the instrument, a power supply coupled to the output stage for

10   supplying power to the output stage, and control circuitry including sensing means for deriving a sensing signal representative of the radio frequency peak output voltage developed across the output lines, wherein the output stage comprises a series-resonant output circuit coupled to the output lines and a switching means coupled to the resonant output circuit, and wherein the control circuitry is operable to vary the

15   switching intervals of the switching device to reduce the delivered radio frequency power in response to a predetermined condition of the sensing signal. In a preferred embodiment of the invention, the series-resonant output circuit comprises the series combination of an inductance and a capacitance, and is coupled to the switching means such that a switched radio frequency output waveform is developed across the series

20   combination, the output lines of the generator being coupled to the series-resonant circuit to receive the radio frequency voltage developed across the inductance or the capacitance, preferably the inductance. The series combination may be coupled between the switching means and a ground connection or one of a pair of supply rails of the power supply means, one of the output lines of the generator being coupled to a

25   junction between the inductance and the capacitance, and the other being preferably connected to the said ground connection or one of the said supply rails. With the capacitance connected to the switching means and the inductance connected to the ground connection or supply rail, the output line is preferably connected to the junction of the inductance and capacitance by a coupling capacitance which is of smaller value

30   than the capacitance of the series resonant combination. Alternatively, the switching means may comprise semiconductor switches connected in a bridge configuration, the

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series combinati n being coupled between oppositely phased nodes of the switching means.

In order to achieve rapid power reduction when, for example, liquid in the region of electrodes connected to the generator vaporises, the switching means and control circuitry are so arranged that the on-time of the switching means can be reduced to the extent of causing at least a 50% reduction in delivered output power within 100μs of a predetermined radio frequency peak output voltage threshold having been reached. (The term "peak output voltage" in this context includes voltages measured on a peak-to-peak basis). In other words, the generator is responsive to a sensing signal representing peak or peak-to-peak output voltage levels. The switching means may comprise a pair of electronic switches connected in a push-pull series arrangement between the power supply rails, with the series-resonant output circuit coupled to the connection between the electronic switches. Thus, to reduce the output power, the on-time of each switch, which is typically a power MOSFET, is reduced during respective radio frequency half cycles to cause the required power reduction.

By causing a control overshoot in the sense of reducing the output power by a greater amount than the increase needed to produce vaporisation, vapour bubbles are allowed to collapse. This allows surgery to be performed in a conductive fluid field, in particular in a saline solution. Large and rapid changes in load impedance can occur substantially without causing unwanted electrosurgical effects. For example, when it is desired to produce electrosurgical desiccation, any increase in impedance due to vaporisation of surrounding saline in the region of an electrode of the instrument which might otherwise lead to unwanted arcing at the required power level for effective desiccation can be largely prevented. When electrosurgical tissue cutting or tissue vaporisation is required, output voltage limitation can be used to prevent electrode burning and/or excessive tissue vaporisation.

To avoid overloading of semiconductor power devices used in the switching means, the switching means are preferably driven by an oscillator operating at a frequency

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different from the resonant frequency of the series-resonant output circuit. By operating the oscillator at an excitation frequency higher than the resonant frequency of the series resonant output circuit, the available power at comparatively high impedances associated with cutting or vaporisation can be increased, while operating the oscillator so as to excite the resonant circuit at a frequency lower than its resonant frequency is more suited to electrosurgical desiccation which involves comparatively low load impedances.

The control circuitry referred to above is preferably arranged such that at least a 50% reduction in output power is brought about in a period of less than 20µs after the output voltage reaches the predetermined sensing signal threshold by reducing the period of conduction of the electronic switches during individual cycles of the radio frequency output signal. Such alteration in the period of conduction is advantageously achieved independently of any variation in supply voltage. In practice, the reduction in output power is brought about using a single control variable, i.e. the peak output voltage or peak-to-peak output voltage independently of supply voltage and independently of the delivered output power which, of course, varies according to load impedance and supply voltage. Thus, triggering of a power reduction occurs at the same preset output voltage threshold but at different output power and load impedance values, according to circumstances.

The technique of directly controlling the radio frequency output stage can be performed by repeatedly producing, firstly, a rapid reduction in the cycle-by-cycle conduction period of the power device from a peak level to a trough level when the output threshold is reached, followed by, secondly, a progressive increase in the conduction period until the conduction period again reaches its peak level, the radio frequency output voltage being monitored during the progressive increase.

The output stage preferably includes an output resonant circuit having a Q which is sufficiently high to remove switching noise from the switching device or devices of the stag without unduly slowing the response to th output voltage reaching the

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predetermined threshold. Typically, the Q is at least 1 and is also sufficient to achieve a crest factor below 1.5, the crest factor being the ratio of the peak and r.m.s. values of the output voltage waveform.

5   Other aspects of the invention include a generator for underwater electrosurgery having an output impedance in the range of from 100 ohms to 250 ohms, and preferably between 130 and 190 ohms. Such a generator has its radio frequency output stage operable to produce a CW (continuous wave) output, i.e. with a 100% duty cycle or without on/off pulse width modulation at a frequency lower than the r.f. oscillation

10   frequency. In effect, the output stage may operate as an open loop stage.

According to a second aspect of the invention, there is provided an electrosurgical system including a generator for generating radio frequency power and an electrosurgical instrument having at least one electrode for use immersed in a

15   conductive liquid, wherein the generator comprises an output stage including at least one radio frequency power device, a series-resonant output circuit, and at least a pair of output connections arranged to receive radio frequency power from the power device, one of the pair of connections being connected to the said electrode, and wherein the generator further comprises a control stage operable to reduce the conduction time of

20   the power device during individual radio frequency cycles in response to a sensing signal representative of the voltage presented to the generator across the output connections exceeding a predetermined sensing signal threshold value, whereby the radio frequency power delivered to the electrode structure is rapidly reduced when the conductive liquid is vaporised. The electrode structure may include a distal treatment

25   electrode and a liquid contact electrode spaced proximally from the distal electrode, both electrodes being for use surrounded by the conductive liquid and each being connected to a respective one of the pair of output connections the control stage being operable to reduce the reduction time of the power device when the conductive liquid at the distal electrode is vaporised. The electrosurgical instrument may provide an

30   electrode structure having juxtaposed first and second electrodes for immersion in the conductive liquid, th first and second electrodes respectively forming a tissue contact

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electrode at an extreme distal end of the instrument and a return electrode proximally spaced from the tissue contact electrode.

The system may be switchable between at least a tissue desiccation mode and a tissue
5   cutting or vaporisation mode using a mode selection control. In this case the control stage is operable automatically to adjust the radio frequency power suppled to the electrode structure to limit the peak generator output voltage to a first value when the desiccation mode is selected and to at least one second value when the cutting or vaporisation mode is selected, the second value or values being higher than the first .
10   value. The first and second values are advantageously in the ranges of from 150V to 200V, and from 250V to 600V respectively, these voltages being peak voltages.

The mode selection control may be coupled to the generator oscillator driving the power device so that, in the tissue desiccation mode, the oscillation frequency of the
15   oscillator is lower than the resonant frequency of the series-resonant output circuit, yet in the tissue cutting or vaporisation mode is higher than that resonant frequency for improved output power at comparatively low and comparatively high impedances respectively, as mentioned above.

20   According to a third aspect of the invention, there is provided an electrosurgical generator for supplying radio frequency power to an electrosurgical instrument, the generator comprising a radio frequency output stage having at least a pair of electrosurgical output connections for the delivery of radio frequency power to the instrument, a radio frequency oscillator for feeding a radio frequency signal to the
25   output stage, and control circuitry including sensing means for deriving a sensing signal representative of the radio frequency signal delivered from the output connections, wherein the output stage comprises a series-resonant output circuit coupled to the output connections, the resonant frequency of the series-resonant output circuit being different from the operation frequency of the oscillator, and wherein the
30   control circuitry provides a feedback signal for controlling the delivered radio frequency power.

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The invention will now be described by way of example with reference to the drawings in which:-

Figure 1 is a diagram showing an electrosurgical system in accordance with the
5   invention;

Figure 2 is a fragmentary view of a first electrode assembly for tissue desiccation, shown in use and immersed in a conductive liquid;

10   Figure 3 is a load characteristic graph illustrating the variation in load impedance produced by an electrode assembly such as that shown in Figure 2 when used in a conductive liquid, according to the delivered output power;

Figure 4 is a fragmentary view of a second electrode assembly for tissue vaporisation,
15   shown in use immersed in a liquid;

Figure 5 is a combined circuit and block diagram of a generator in accordance with the invention;

20   Figure 6 is a waveform diagram;

Figure 7 is a block diagram of part of the control circuity of the generator of Figure 5;

Figure 8 is a power v. load impedance graph relating to the generator when operating
25   in a desiccation mode;

Figure 9 is a similar graph applicable to a tissue cutting or vaporisation mode; and

Figure 10 is a combined circuit and block diagram of an alternative generator in
30   accordance with the invention.

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The preferred embodiment of the present invention is intended to form bipolar electrosurgery with electrodes immersed in a conductive liquid medium such as normal saline. Electrosurgery is performed using a system comprising a generator and an instrument, the instrument having a dual-electrode structure with the saline acting

5   as a conductor between the tissue being treated and one of the electrodes, hereinafter called the "return electrode". The other electrode is applied directly to the tissue. This other electrode is hereinafter called the "active electrode".

Such a system is shown in Figure 1. The generator 10 has an output socket 10S

10   providing a radio frequency (RF) output for an instrument in the form of a handpiece 12 via a connection cord 14. Activation of the generator may be performed from the handpiece 12 via a control connection in cord 14 or by means of a footswitch unit 16, as shown, connected separately to the rear of the generator 10 by a footswitch connection cord 18. In the illustrated embodiment, footswitch unit 16 has two

15   footswitches 16A and 16B for selecting a desiccation mode and a vaporisation mode of the generator respectively. The generator front panel has push buttons 20 and 22 for respectively setting desiccation and vaporisation power levels, which are indicated in a display 24. Push buttons 26 are provided as an alternative means for selection between desiccation and vaporisation modes.

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Handpiece 12 mounts a detachable electrode assembly 28 having a dual electrode structure, as shown in the fragmentary view of Figure 2.

Figure 2 is an enlarged view of the distal end of electrode assembly 28. At its extreme

25   distal end the assembly has an active electrode 30 which, in this embodiment, is formed as a series of metal filaments connected to a central conductor 32. The filaments may be made of stainless steel. Proximally of the active electrode 30 and spaced from the latter by a longitudinally and radially extending insulator 34 is a return electrode 36. The return electrode 36 is arranged coaxially around the inner conductor

30   32 as a sleeve 38 which extends as a tubular shaft 40 to the proximal end of the assembly 28 where it is connected in the handpiece 12 to conductors in the connection

cord 14. Similarly, the inner conductor 32 extends to the handpiece and is connected to a conductor in cord 14. The electrode assembly 28 has an insulating sheath 42 which covers shaft 40 and terminates proximally of the insulator 34 to leave the distal end of shaft 40 exposed as the return electrode 36.

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In operation as a desiccation instrument, the electrode assembly 28 is applied as shown in Figure 2 to the tissue 44 to be treated, the operation site being immersed in a normal saline (0.9%w/v) solution, here shown as a drop 46 of liquid surrounding the distal end portion of the electrode assembly 28. The liquid immerses both the active electrode 30 and the return electrode 36.

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Still referring again to Figure 2, the metallic filaments forming the active electrode 30 are all electrically connected together and to the inner conductor 32 of the electrode assembly to form a unitary active electrode. Insulator 34 is an insulating sleeve, the distal end portion of which is exposed proximally of the exposed part of the active electrode 30. Typically, this sleeve is made of a ceramic material to resist damage from arcing. The return electrode terminates at a point short of the end of the insulator 36 so that it is both radially and axially spaced from the active, or tissue contact, electrode 30. The surface area of the return electrode is considerably greater than that of the active electrode 30. At the distal end of the electrode assembly, the diameter of the return electrode is typically in the region of from 1mm to 3mm, with the longitudinal extent of the exposed part of the return electrode being typically between 1mm and 5mm with the longitudinal spacing from the active electrode being between 1mm and 5mm.

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In effect, the electrode assembly is bipolar, with only one of the electrodes (30) actually extending to the distal end of the unit. This means that the return electrode, in normal circumstances, remains spaced from the tissue being treated and a current path exists between the two electrodes via the tissue and the conductive liquid which is in contact with the return electrode 36.

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The conductive liquid 46 may be regarded, as far as the delivery of bipolar
electrosurgical energy is concerned, as a low impedance extension of the tissue. Radio
frequency currents produced by the generator 10 flow between the active electrode 30
and the return electrode 36 via the tissue 44 and the immersing conductive liquid 46.

5   The particular electrode arrangement shown in Figure 2 is most suitable for tissue
desiccation.

The axial as well as radial separation between the electrodes avoids the small spacing
of the conventional bipolar arrangement in which both electrodes are tissue-contacting.

10   As a result, there is less danger of unwanted arcing across the insulation surface, which
allows comparatively high power dissipation for desiccation treatment, and, in the case
of tissue cutting or vaporisation, prevents excessive arcing which can lead to inter-
electrode insulation damage.

15   The immersing saline solution may be provided from a conduit (not shown) forming
part of the instrument 12. Thus, the invention may take the form of an electrosurgical
system for the treatment of tissue immersed in a conductive fluid medium, comprising
an electrosurgical instrument having a handpiece and an instrument shaft, and, on the
end of the shaft, an electrode assembly, the assembly comprising a tissue contact

20   electrode which is exposed at the extreme distal end of the instrument, and a return
electrode which is electrically insulated from the tissue contact electrode and has a
fluid contact surface spaced proximally from the exposed part of the tissue contact
electrode, the system further comprising a radio frequency generator coupled to the
electrode assembly of the instrument, a reservoir of electrically conductive fluid, such

25   as the normal saline solution, and a conduit, typically and integral part of an
endoscope, for delivering the liquid from the reservoir to the region of the electrode
assembly. Pressure for delivering the liquid may be provided by a pump forming part
of the apparatus.

30   Since in this embodiment of electrode assembly 28, the active electrode 30 is made of
stainless steel filaments in the form of a brush, the electrode is flexible, providing a

reproducible tissue effect which is comparatively independent of the application angle of the electrode to the tissue surface. The flexibility of the electrode 30 also results in a differential contact area of the active electrode dependent on the applied pressure, allowing variations in the breadth of desiccation over the surface of the tissue,

5   reducing procedure time.

Desiccation occurs by virtue of radio frequency currents passing between the active electrode 30 and the conductive liquid 46 via the outer layer of the tissue 44 immediately beneath and in an area surrounding the active electrode 30. The output

10   impedance of the generator is set at a level commensurate with the load impedance of the electrode assembly when used as shown in Figure 2 with both electrodes in contact with the conductive liquid 46. In order to sustain this matched state for tissue desiccation, the output power of the generator is automatically controlled in a manner which will be described below so that vapour bubbles of significant size are

15   substantially prevented from appearing at the active electrode 30, thereby avoiding a consequent increase in load impedance. In this way, the active electrode can be continually wetted by the conductive liquid so that, whilst the tissue water is removed by thermal desiccation, the impedance reaches an upper limit corresponding to the point at which the conductive liquid starts to boil. As a result, the system is able to

20   deliver high power levels for desiccation without unwanted conductive liquid vaporisation leading to unwanted tissue effects.

The electrical behaviour of the electrode assembly when the electrodes 30 and 36 are immersed in the conductive liquid 46 is now considered with reference to the graph of

25   Figure 3.

When power is first applied, there is presented to the generator an initial load impedance r which is governed by the geometry of the electrode and the electrical conductivity of the conductive liquid. The value of r changes when the active

30   electrode touches the tissue. The higher the value of r, the greater is the propensity of the conductive liquid to vaporise. As power is dissipated in the tissue and the

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conductive liquid, the conductive liquid increases in temperature. In the case of normal saline, the temperature coefficient of conductivity is positive and the corresponding impedance coefficient is therefore negative so that the impedance initially falls. Thus, the curve in Figure 3 indicates a fall in load impedance as the

5 delivered power is increased, the impedance falling through point A to a minimum at point B, at which point saline in immediate contact with the electrode reaches boiling point. Small vapour bubbles now form on the surface of the active electrode and the impedance starts to rise as shown by the curve rising from point B to point C. Thus, once the boiling point has been reached, the arrangement displays a dominant positive

10 power coefficient of impedance.

As the vapour bubbles form, there is an increase in the power density at the remaining active electrode to saline interface (the exposed area of the active electrode not covered by vapour bubbles) which further stresses the interface, producing more vapour

15 bubbles and thus even higher power density. This is a runaway condition, with an equilibrium point only occurring once the electrode is completely enveloped in vapour. Thus, for a given set of variables, there is a power threshold corresponding to point C at which this new equilibrium is reached.

20 In the light of the foregoing, it will be appreciated that the region between points B and C in Figure 3 represents the upper limit of desiccation power which can be achieved.

Upon formation of an electrode-enveloping vapour pocket, the impedance elevates to about 1kΩ, as shown by point D in Figure 3, the actual impedance value depending on

25 a number of system variables. The vapour is then sustained by discharges across the pocket between the active electrode and the vapour/saline interface.

This state of affairs is illustrated by the diagram of Figure 4 which shows an alternative electrode assembly 28A having a hemispherical or ball electrode 30A in

30 place of the brush electrode 30 of the embodiment of Figure 2. As before, the return

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electrode 36A is proximally spaced from the active electrode 30A by an intervening insulator 34A. The ball electrode is preferred for tissue vaporisation.

Once in the vaporisation equilibrium state, the vapour pocket, shown by the reference

5   50 in Figure 4, is sustained by discharges 52 across the vapour pocket between the active electrode 30A and the vapour to saline interface. The majority of power dissipation occurs within this pocket with consequent heating of the active electrode. The amount of energy dissipation in this conduction is a function of the delivered power. It will be noted from Figure 3 that the vaporisation mode, indicated by the

10   dotted boundary lines, can be sustained at much lower power levels than are required to bring about formation of the vapour pocket. The impedance/power characteristic consequently displays hysteresis. Once the vaporisation mode has been established, it can be maintained over a comparatively wide range of power levels, as shown by the inclined part of the characteristic extending on both sides of point D. However,

15   increasing the delivered output power beyond that represented by point D causes a rapid rise in electrode temperature, potentially damaging the electrode. To collapse the vapour pocket and to return to desiccation mode requires a significant power reduction back to point A, direct contact between the active electrode and the saline being reestablished and the impedance falling dramatically. The power density at the active

20   electrode also falls so that the temperature of the saline now falls below boiling point and the electrode is then once again in a stable desiccation equilibrium.

The generator to be described hereinafter has the ability to sustain both the desiccation mode and the vaporisation mode. Whilst in general the electrode assemblies illustrated

25   in Figures 2 and 4 can be used in either mode, the brush electrode of Figure 2 is preferred for desiccation due to its wide potential area of coverage, and the ball electrode of Figure 4 is preferred for vaporisation due to its small active electrode/return electrode surface area ratio. As can be seen from Figure 4, tissue vaporisation occurs when the vapour pocket 50 intersects the tissue surface, with the

30   electrode assembly preferably being held spaced above the tissue surface by a small distance (typically 1mm to 5mm).

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The runaway condition which occurs when the delivered power reaches the lev 1
shown by point C in Figure 3 is exacerbated if the generator has a significant output
impedance, because the output voltage can then suddenly rise. With increased power
dissipation and without the presence of the cooling liquid around the active electrode

5   30, the electrode temperature rises rapidly with consequent damage to the electrode.
This also produces uncontrollable tissue disruption in place of the required desiccation.
For this reason, the preferred generator has an output source impedance which,
approximately at least matches the load impedance of the electrode structure when
wetted.

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The preferred generator now to be described allows both desiccation electrosurgery
substantially without unwanted cell disruption, and electrosurgical cutting or
vaporisation substantially without electrode burning. Although intended primarily for
operation in a conductive liquid distension medium, it has application in other

15   electrosurgical procedures, e.g. in the presence of a gaseous distension medium, or
wherever rapid load impedance changes can occur.

Referring to Figure 5, the generator comprises a radio frequency (RF) oscillator 60
which operates at above or below about 400 kHz, with any frequency from 300 kHz

20   upwards into the HF range being feasible. Oscillator 60 drives a power output stage 62
comprising two power MOSFETs T_1, T_2 coupled in push-pull arrangement between
two supply rails V_s and 0V. The power supply rails are driven by a power supply
stage 64.

25   Transistors T_1 and T_2 are driven in a switching mode by a pulse width controller 64
which is, itself, driven by the oscillator 60. Thus each transistor T_1, T_2 receives one
gating pulse during each cycle of the RF oscillator 60, the pulses being timed such that
T_1 is switched on during oscillator half cycles of one polarity, while T_2 is switched on
during oscillator half cycles of the opposite polarity, and the width of the gating pulses

30   is controlled according to the required output power.

Coupled to the junction between the two electronic switches represented by transistors T_1, T_2 is a series-resonant output circuit comprising a capacitor C_r and an inductor L_r. The series resonant frequency of these two components is about 400 kHz, but generally different from the frequency of operation of oscillator 60. Coupled to the junction between capacitor C_r and inductor L_r via a coupling capacitor C_c is one of end of a primary winding of an output isolation transformer 65 feeding the output terminals 66, 68 of the generator. The other end of the primary winding is coupled to one of the supply rails, in this case the ground connection 0V. Coupling capacitor C_c is smaller than capacitor C_r.

The connection of the series-resonant circuit C_r, L_r to the switches is direct; there is no intervening second series resonant circuit such as a parallel-resonant circuit, and the load impedance presented to the switches (when its variation is considered with respect to excitation frequency) exhibits a predominant minimum at the resonant frequency of the series-resonant circuit.

In parallel with the source and drain connections of each transistor T_1, T_2 is a respective energy recovery diode D_1, D_2.

Switching of transistors T_1, T_2 in the above-described manner causes the application to the junction 65 between the transistors of a RF excitation voltage having a waveform as shown in Figure 6. A corresponding sinusoidal waveform is produced at the junction of the two series-resonant components C_r and L_r, the amplitude of which depends on the difference in frequency between the oscillator frequency and the frequency of resonance, and on the impedance of the load 70 connected across the output terminals 66, 68.

Coupled across the output connections 66, 68 is a voltage threshold detector 72 having an output 72A coupled to an "on" time control circuit 74.

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In operation of the generator, power is applied to the power supply 64 when electrosurgical power is demanded by the surgeon operating an activation switch arrangement which may be provided on a handpiece or footswitch (see Figure 1). A constant output voltage threshold is set independently of the supply voltage via input

5   72B according to control settings on the front panel of the generator (see Figure 1). Typically, for desiccation or coagulation the threshold is set at a desiccation threshold value between 150 volts and 200 volts. When a cutting or vaporisation output is required, the threshold is set to a value in the range of from 250 or 300 volts to 600 volts. These voltage values are peak values. Their being peak values means that for

10   desiccation at least it is preferable to have an output RF waveform of low crest factor to give maximum power before the voltage is clamped at the values given. Typically a crest factor of 1.5 or less is achieved.

When the generator is first activated, the status of the control input 64I of the pulse

15   width controller 64 (which is connected to the "on" time control circuit 74) is "on", such that the transistors T1, T2 which form the output stage 62 are each switched on for a maximum conduction period during each oscillation cycle which may be a full half cycle of the oscillator output. Providing the delivered power is sufficiently high, the temperature of the liquid medium surrounding the electrodes of the electrosurgical

20   instrument (or within a gaseous medium, the temperature of liquids contained within the tissue) may rise to such an extent that the liquid medium vaporises, leading to a rapid increase in load impedance and a consequent rapid increase in the applied output voltage across terminals 12. This is an undesirable state of affairs if a desiccation output is required. For this reason, the voltage threshold for a desiccation output is set

25   to cause a trigger signal to be sent to the "on" time control circuit 74 when the threshold is reached. The "on" time control circuit 74 has the effect of virtually instantaneously reducing the width of the gating pulses produced by controller 64 thereby virtually instantaneously reducing the "on" time of the RF switching device T_1, T_2.

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Subsequent control of the "on" time of the devices T_1, T_2 in individual cycles of the oscillator 60 will be understood by considering the internal configuration of the "on" time control circuit 74 which is shown in Figure 7. The circuit comprises an RF sawtooth generator 80 (synchronised at the RF oscillation frequency by a synchronisation signal derived from the oscillator and applied to a synchronisation input 74I), and a ramp generator 82 which is reset by a reset pulse from the output 72B of the voltage threshold detector 72 (see Figure 5) produced when the set threshold voltage is reached. This reset pulse is the trigger signal referred to above. The "on" time control circuit 74 further comprises a comparator 84 for comparing the sawtooth and ramp voltages produced by the sawtooth and ramp generators 80 and 82 to yield a square wave control signal for application to the input 64I of the pulse width controller 64. As shown by the waveform diagrams in Figure 7, the nature of the sawtooth and ramp waveforms is such that the mark-to-space ratio of the square wave signal applied to the controller 64 progressively increases after each reset pulse. As a result, after a virtually instantaneous reduction in "on" time on detection of the output voltage reaching the set voltage threshold, the "on" time of the RF oscillator is progressively increased back to the original maximum value. This cycle is continuously repeated until the temperature of the liquid surrounding the electrodes reduces to such a level such that vaporisation no longer occurs.

The output voltage of the generator is important to the mode of operation. In fact, the output modes are defined purely by output voltage, specifically the peak output voltage. The absolute measure of output voltage is only necessary for multiple term control. However, a simple single term control (i.e. using one control variable) can be used in this generator in order to confine the output voltage to predetermined limit voltages. Thus, the voltage threshold detector 72 shown in Figure 5 compares the RF peak output voltage with a preset DC threshold level, and has a sufficiently fast response time to produce a reset pulse for the "on" time control circuit 74 within one RF half cycle.

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When the series-resonant output circuit is excited by switching of transistors T_1, T_2 at a frequency near resonance, the amplitude of the voltage at the junction between transistors T_1, T_2 can exceed the supply voltage. In this condition, when both transistors are turned off, diodes D_1, D_2 recover energy from the resonance circuit into

5   the supply. Intermediate levels of excitation are possible by using less than half-wave switching of the push-pull devices, the on-time providing excitation, the off-time providing power recovery and damping.

Before considering the operation of the generator further, it is appropriate to refer back

10   to the impedance/power characteristic of Figure 3. It will be appreciated that the most critical control threshold is that applicable during desiccation. Since vapour bubbles forming at the active electrode are non-conducting, the saline remaining in contact with the electrode has a higher power density and consequently an even greater propensity to form vapour. This degree of instability brings about a transition to a

15   vaporisation mode with the same power level due to the runaway increase in power density at the active electrode. As a result, the impedance local to the active electrode rises. Maximum absorbed power coincides with the electrode condition existing immediately before formation of vapour bubbles, since this coincides with maximum power distribution and the greatest wetted electrode area. It is therefore desirable that

20   the electrode remains in its wetted state for the maximum desiccation power. Use of voltage limit detection brings about a power reduction which allows the vapour bubbles to collapse which in turn increases the ability of the active electrode to absorb power. For this reason, the generator described in this specification includes a control loop having a large overshoot, in that the feedback stimulus of the peak voltage

25   reaching the predefined threshold causes a large instantaneous reduction in power by causing a reduction in peak output voltage to a level significantly below the peak output voltage level set by the threshold detector 72. This control overshoot ensures a return to the required wetted state.

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In the generator described above with reference to Figures 5, 6 and 7, power reduction in response to voltage threshold detection takes place through an instantaneous reduction in RF energy supplied to the series-resonant output circuit.

5   In the preferred embodiment, the instantaneous power reduction is by at least three quarters of available power (or at least half voltage) from the DC power supply and preferably by more. Thus, a high speed response is obtained in the RF stage itself.

In a typical desiccation episode the output voltage increases with increasing load
10   impedance to a point at which the output voltage threshold is reached, whereupon the above-described instantaneous reduction in output stage "on" time occurs. This produces a rapid decrease in the RF output voltage, followed by a progressive increase, again as described above. When the output voltage again reaches the threshold voltage, the "on" time of the oscillator is once again instantly reduced and then
15   progressively increased, so that the output voltage waveform repeats its previous pattern. Yet again, the threshold voltage is reached, again the output voltage is instantly reduced, and again the "on" time is allowed to increase, and so on until the conditions at the operation site change such that vapour is no longer formed.

20   It will be seen, then, that the control circuitry 74, 64 (Figure 5) operates dynamically to control the output voltage both sufficiently rapidly and to a sufficient degree to maintain the voltage at a level consistent with, in this case, the level required for desiccation without tissue disruption due to arcing. The same technique can be used with a different threshold voltage to limit the output voltage to prevent electrode
25   burning and/or excessive tissue vaporisation. In the latter case, the voltage limit may be set to a level between 250 volts (preferably 300 volts) and 600 volts.

Due to the high power density at the active electrode during the vaporisation mode, the great majority of delivered power is dissipated in the proximity of the electrode. In the
30   vaporisation mode, it is desirable that a minimum of saline heating occurs, but that any tissue which encroaches the vapour boundary of the active lectrode is vaporised. In

20

the vaporisation mode, the vapour is sustained by arcs within the vapour pocket as described above with reference to Figure 4. Increasing the output voltage during vaporisation results in increased volume of tissue removal due to the increased size of the vapour pocket. Collapse of the vapour pocket during tissue vaporisation has

5   greater consequence, due to the increased necrosis as a result of the greater power dissipation in the surrounding saline. Vapour pocket collapse can be prevented by, firstly, arranging for the electrode impedance in vaporisation mode to be such that the instrument is in an unmatched condition as regards impedance, with result that the resonant output circuit Q is high and the output voltage does not change so rapidly as

10   with lower load impedances and, secondly, the active electrode has a significant heat capacity that sustains the vapour pocket for a significant period.

An unwanted increased in the size of the vapour pocket can be prevented by limiting the peak output voltage during the vaporisation mode, which may be conveniently

15   carried out by substituting a different threshold value for the voltage threshold detector 72 (see Figure 5) when in the vaporisation mode.

The circuitry of the voltage threshold detector 72, and "on" time control circuit 74 (shown in Figure 5) in the preferred generator in accordance with the invention is as

20   described and shown in our co-pending European Patent Application No. 96304558.8.

As has been described above, different threshold voltages are applicable to desiccation on the one hand and cutting or tissue vaporisation on the other hand. Accordingly, the generator includes a mode selection control 86, as shown in Figure 5. In practice, this

25   may be part of a microprocessor control system (not shown) producing outputs which depend on handpiece or foot-operated switch settings. Thus, for a desiccation output, the mode selection control sets the voltage threshold of threshold detector 76 to a first value via input 72B, whilst for cutting or vaporisation, a different, higher threshold value is set. Improved results can also be obtained by setting the RF oscillator

30   frequency to different values according to whether desiccation or cutting/vaporisation are required. Thus, for desiccation, the mode selection control applies a frequency

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control signal to the RF oscillator via control input 60I to set the oscillator frequency below the resonant frequency of the series-resonant combination C_r, L_r. Conversely, when cutting or tissue vaporisation is required, the RF oscillator is set to a frequency higher than the resonant frequency. The lower frequency has the effect of skewing the

5 power versus load impedance characteristic so as to increase the power available at low impedances, as encountered during desiccation. The higher oscillator frequency has the effect of flattening the power versus load impedance curve, favouring higher impedances, as encountered when the immersing fluid vaporises. These power/load impedance variations are shown diagrammatically in Figures 8 and 9, in which f_E and

10 f_r represent the excitation (i.e. oscillator) frequency and the resonant frequency respectively.

Blended modes can be used by constantly alternating between desiccation and cut states or by altering the position of the thresholds.

15

An alternative generator to that described above with reference to Figure 5 may be used, having an output stage with switching means in bridge configuration, as shown in Figure 10. In this case, the switching devices comprise four power MOSFETs arranged in two pairs of two transistors, each pair being arranged in a push-pull

20 configuration. The first pair is shown in Figure 10 as transistors T3 and T4, and the second pair as transistors T5 and T6. The series-resonant output circuit comprising capacitor C_r and conductor L_r is coupled between the respective junctions of the two pull-push pairs T3, T4 and T5, T6 so that when these pairs are driven in phase opposition by a pulse width and phase controller circuit 64, the radio frequency power

25 signal is applied across the series-combination C_r, L_r. As in the generator of Figure 5, the output to an electrosurgical instrument is taken from across the inductor L_r via a coupling capacitor C_c and an isolation transformer 65, the transformed radio frequency output voltage appearing at terminals 66, 68 for connection of an electrosurgical load 70. In other respects, this alternative generator is similar to the generator described

30 above with reference to Figure 5, and common reference numerals for the common parts are used in Figures 10 and 5 respectively. The voltage waveform generated

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across the series-resonant circuit C_r, L_r typically has the same waveform as that
developed by the generator of Figure 5, i.e. as shown in Figure 6. However, in the
case of this alternative generator, by incorporating a phase control function in the
circuit 64 driving the switching transistors T3 to T6, the phase difference between the
drive signals applied to the respective pairs T3, T4, and T5, T6 can be varied from the
maximum value of 180° downwards so that the output power is reduced. This
constitutes an additional variable for varying output power. Indeed, when required, the
phase difference can be reduced to such an extent that the output power is zero, which
means that, for example, the supply voltage V_S obtained from power supply 64 can be
maintained constant at all times rather than being used as a secondary means of power
reduction.

To summarise, then, the bridge configuration allows rapid power reduction to be
achieved when the conductive liquid surrounding the instrument electrodes vaporises
not only by reducing the "ON" time of the transistors, but also by varying the relative
phase between the two transistor pairs downwards from 180°. It is also possible to
alter the excitation frequency of RF oscillator 60 so as to be further from the resonant
frequency defined by the series-combination of capacitor C_r and inductor L_r as an
additional means of reducing output power.

From a general viewpoint, a radio frequency generator for an electrosurgical system is
provided, the system including an electrode assembly having two electrodes for use
immersed in an electrically conductive fluid. The generator has control circuitry for
rapidly reducing the delivered radio frequency output power by at least 50% within at
most a few cycles of the peak radio frequency output voltage reaching a predetermined
threshold limit. In this way, tissue coagulation can be performed in, for example,
saline without significant steam generation. The same peak voltage limitation
technique can be used in a tissue vaporisation or cutting mode to limit the size of the
steam pocket at the electrodes and to avoid electrode burning. The generator has a
push-pull output stage with a series-resonant output circuit, the output stage being
driven by a radio frequency oscillator at a frequency which, in general, differs from the

resonant frequency of the resonant output circuit. Power control is achieved by varying the ON-time of switching transistors forming the push-pull output pair and by altering the frequency spacing between the excitation frequency and the resonant frequency of the series-resonant output circuit. In an alternative embodiment, a bridge configuration using two push-pull pairs is used, yielding a further power control variable: the relative phase of the driving signals to the respective transistor pairs.

24

CLAIMS

1.   An electrosurgical generator for supplying radio frequency power to an
electrical instrument, the generator comprising a radio frequency output stage
having at least a pair of electrosurgical output lines for the delivery of radio
frequency power to the instrument, a power supply coupled to the output stage
for supplying power to the output stage, and control circuitry including sensing
means for deriving a sensing signal representative of the radio frequency peak
output voltage developed across the output lines, wherein the output stage
comprises a series-resonant output circuit coupled to the output lines and
switching means coupled to the resonant output circuit, and wherein the
control circuitry is operable to vary the switching intervals of the switching
means to reduce the delivered radio frequency power in response to a
predetermined condition of the sensing signal.

2.   A generator according to claim 1, wherein the series-resonant output circuit
comprises the series combination of an inductance and a capacitance, and is
coupled to the switching means such that a switched radio frequency output
waveform is developed across the series combination, the output lines of the
generator being coupled to the series-resonant circuit to receive the radio
frequency voltage developed across the inductance or the capacitance.

3.   A generator according to claim 2, wherein the output lines are coupled to
receive the radio frequency voltage developed across the inductance.

4.   A generator according to claim 2, wherein the series combination is coupled
between the switching means and a ground connection or one of a pair of
supply rails of the power supply means, one of the output lines of the generator
being coupled to a junction between the inductance and the capacitance.

25

5.   A generator according to claim 4, wherein the capacitance is connected between the switching means and the junction, and the inductance is coupled between the junction and the ground connection on the said one supply rail.

5   6.   A generator according to claim 2, wherein the switching means comprise semiconductor switching devices connected in a bridge configuration, the series combination being coupled between oppositely phased nodes of the switching means.

10   7.   A generator according to any of claims 2 to 6, including a series-connected coupling capacitance coupled in a signal path between the series-resonant circuit and one of the output lines.

8.   A generator according to claim 7, wherein the coupling capacitance is of a
15   smaller value than the capacitance of the series-resonant combination.

9.   A generator according to any preceding claim, wherein the switching means comprise a pair of electronic switches connected in a push-pull series arrangement between a pair of supply rails of the power supply, the series
20   resonant output circuit being coupled to the connection between the electronic switches.

10.   A generator according to claim 9, wherein the switching means comprise two pairs of electronic switches in a bridge configuration, each pair connected in a
25   push-pull series arrangement between the supply rails, the series-resonant output circuit being coupled between the connection between the switches of one pair and the connection between the switches of the other pair, the two pairs being arranged so as to be driven with opposite respective phases.

30   11.   A generator according to any preceding claim, wherein the switching means are connected to switch current repeatedly through the resonant output circuit at a

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radio frequency, and wherein the control circuitry is so arranged and coupled to the switching means as to reduce the switching means radio frequency duty cycle sufficiently rapidly to cause at least a 50% reduction in delivered output power within 100μs of a predetermined radio frequency peak output voltage

5   threshold having been reached.

12   A generator according to claim 9 and claim 11, or claim 10 and claim 11, wherein the switching means are connected to switch current repeatedly through the resonant output circuit at a radio frequency, and wherein the

10   control circuitry is so arranged and coupled to the switching means as to reduce the switching means radio frequency duty cycle sufficiently rapidly to cause at least a 50% reduction in delivered output power within 100μs of a predetermined radio frequency peak output voltage threshold having been reached and wherein the control circuitry is arranged to drive each of the

15   electronic switches so as to perform partial cycle switching whereby each has a variable on-time during respective radio frequency cycles, the on-time of both switches being controllable sufficiently rapidly to effect the said at least 50% power reduction within 5 radio frequency cycles.

20   13.   A generator according to claim 11 or claim 12, wherein the control circuitry includes a driver stage including a ramp generator operable to cause a control signal to be applied to the drive stage initially to reduce the said radio frequency duty cycle to cause the at least 50% reduction in power delivered via the output lines, and then progressively to increase the duty cycle at a less rapid

25   rate until the sensing signal indicates that the predetermined voltage threshold has once again been reached.
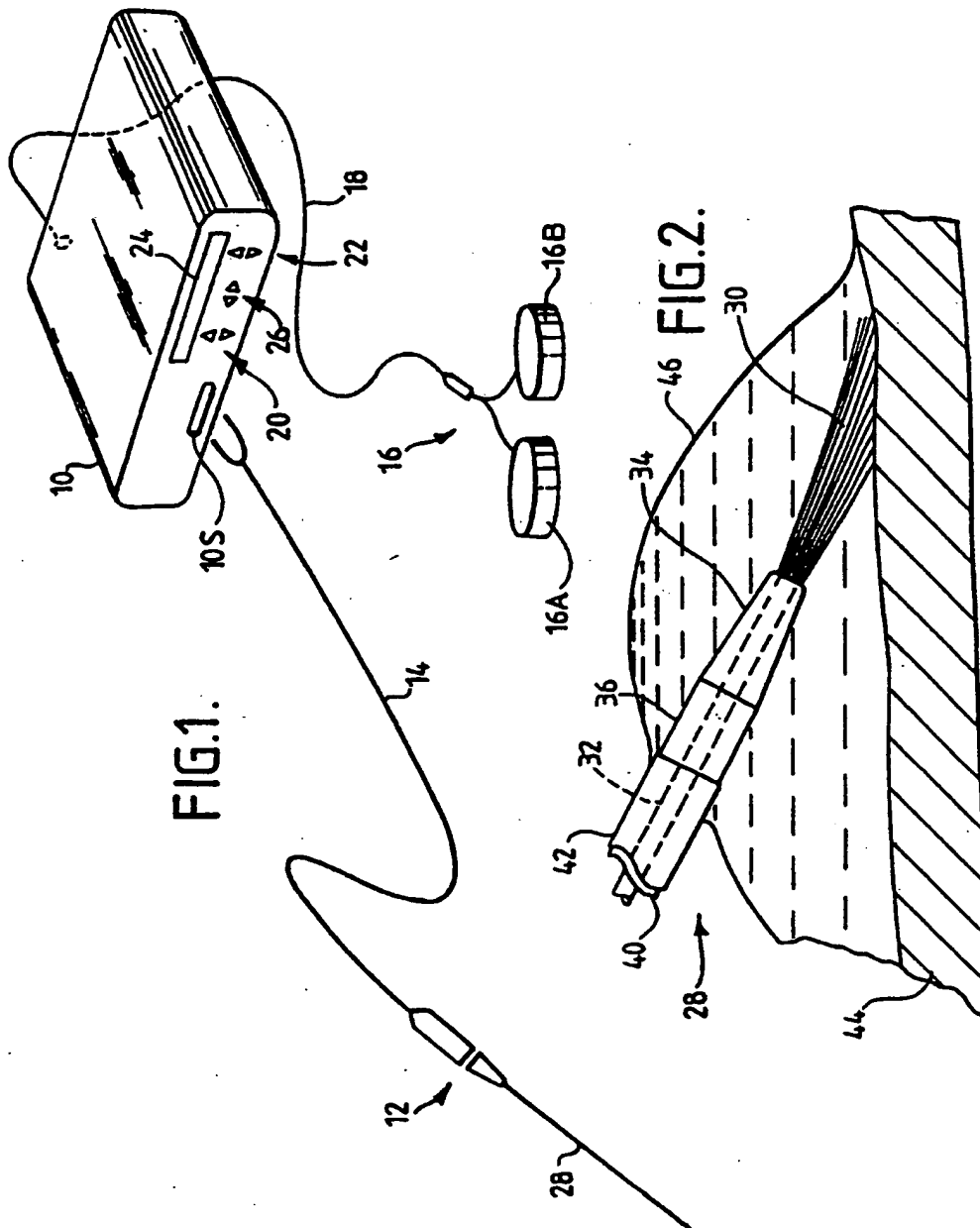
14.   A generator according to any preceding claim, further including an oscillator for driving the switching means, the oscillator being operable at a frequency

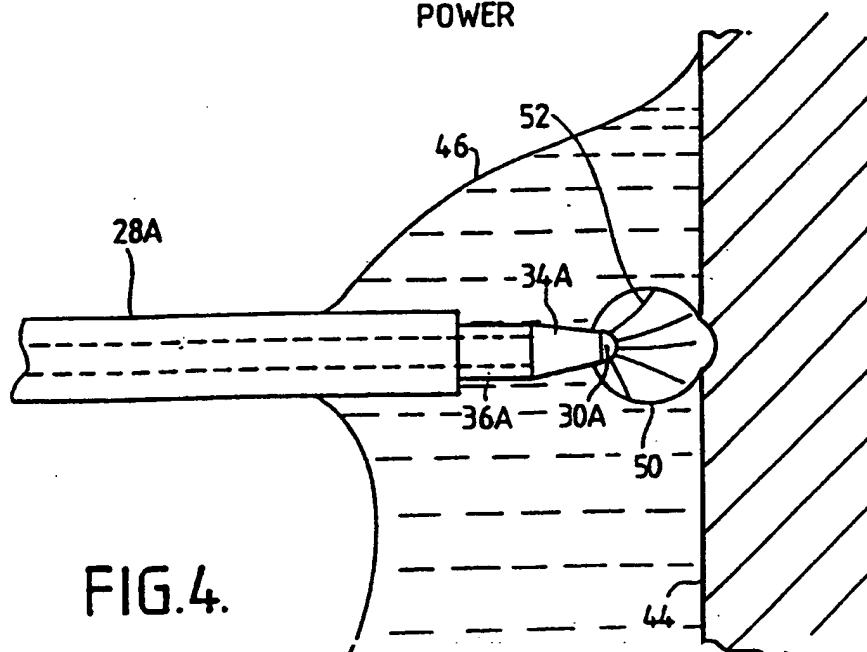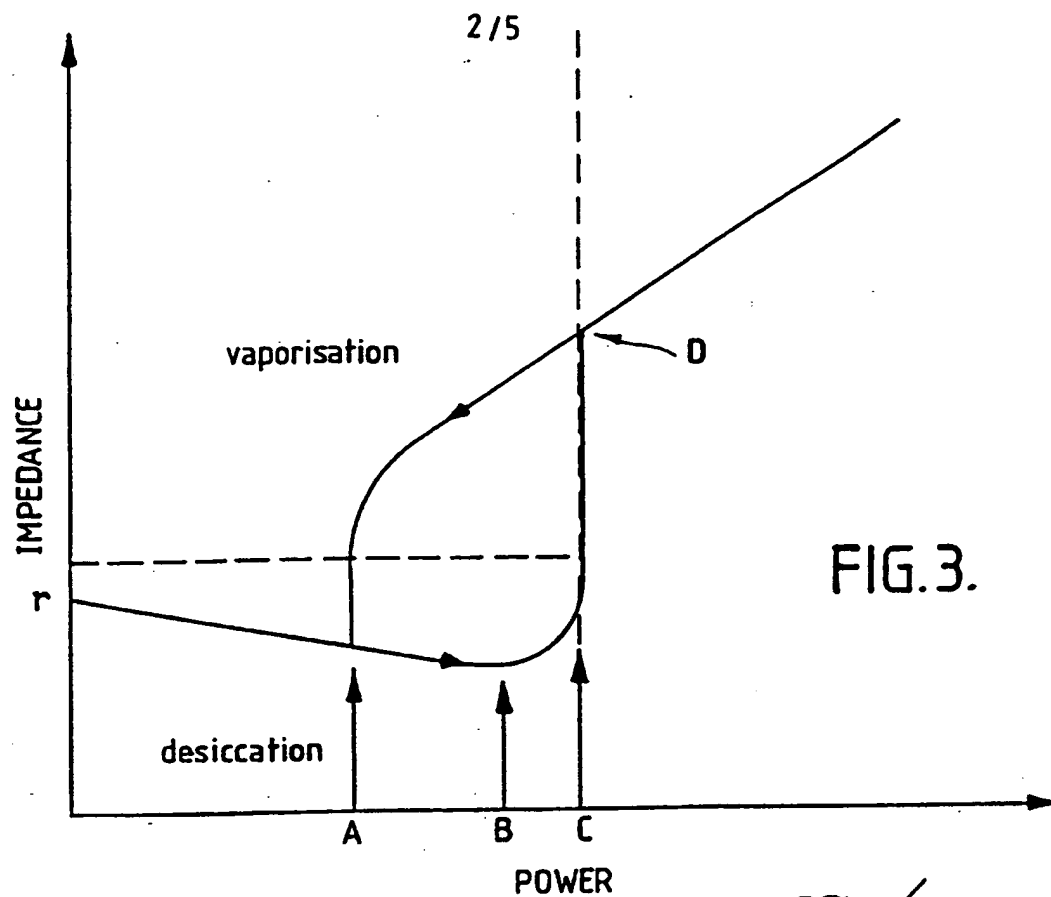30   which is different from the resonant frequency of the series resonant combination.
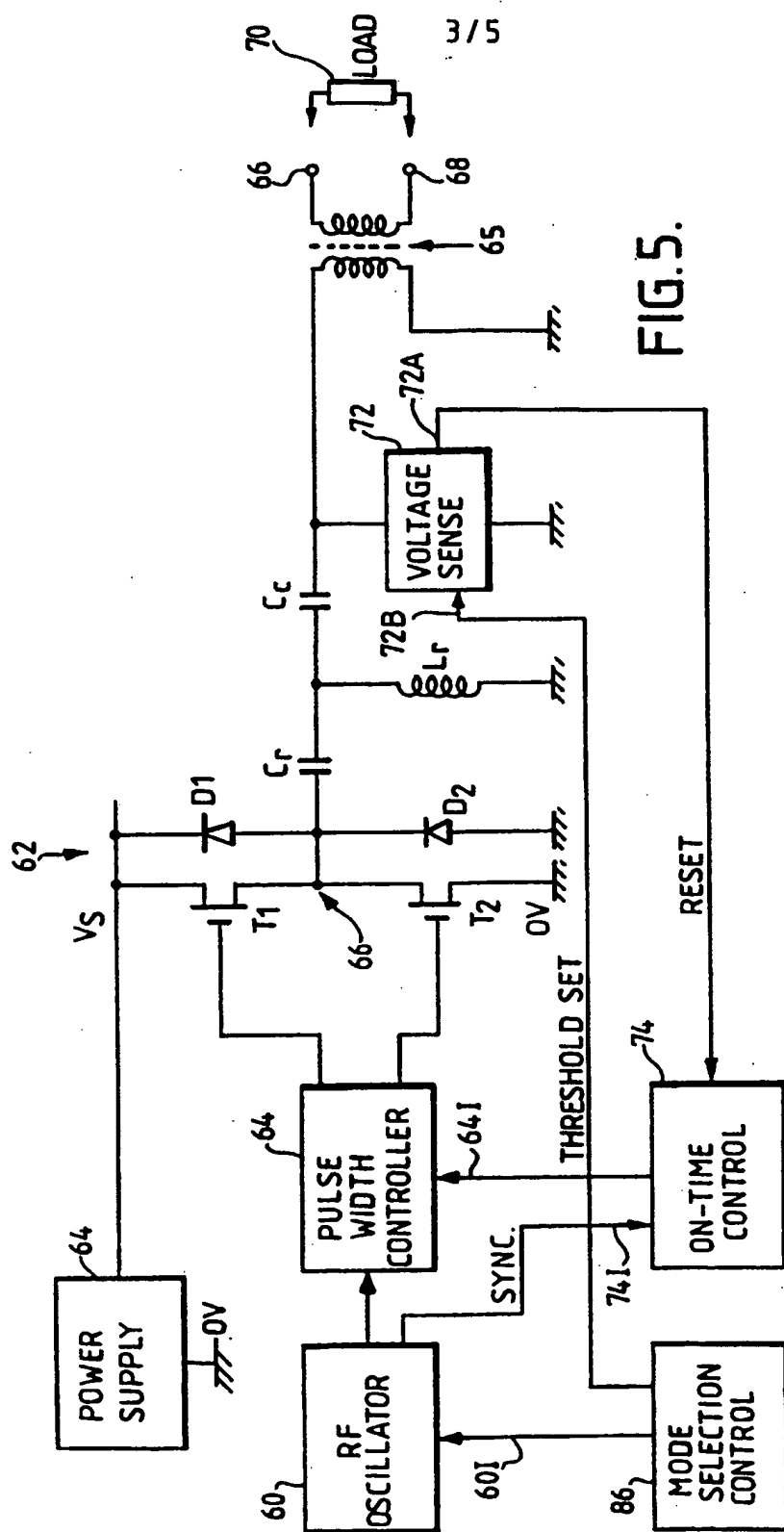
15.   An electrosurgical system including a generator for generating radio frequency power and an electrosurgical instrument having at least one electrode for use immersed in a conductive liquid, wherein the generator comprises an output stage including at least one radio frequency power device, a series-resonant output circuit, and at least a pair of output connections arranged to receive . radio frequency power from the power device, one of the pair of connections being connected to the said electrode, and wherein the generator further comprises a control stage operable to reduce the conduction time of the power device during individual radio frequency cycles in response to a sensing signal representative of the peak output voltage across the output connections exceeding a predetermined sensing signal threshold value, whereby the radio frequency power delivered to the electrode structure is rapidly reduced when the conductive liquid is vaporised.

16.   A system according to claim 15, wherein the electrode structure includes a projecting treatment electrode and a liquid contact electrode spaced from the treatment electrode, both electrodes being for use surrounded by the conductive liquid and each being connected to a respective one of the pair of output connections, the control stage being operable to reduce the conduction time of the power device when the conductive liquid at the treatment electrode is vaporised thereby to cause the collapse of vapour bubbles at the treatment electrode and a decrease in the electrical load impedance.

17.   A system according to claim 16, wherein the electrosurgical instrument has an electrode structure having juxtaposed first and second electrodes for immersion in a conductive liquid, the first and second electrodes respectively forming a tissue contact electrode at an extreme distal end of the instrument and a return electrode proximally spaced from the tissue contact electrode.

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18.   A system according to claim 16 or claim 17, wherein series-resonant circuit coupled between the power device and the output connections has a resonant frequency which is different from the frequency of operation of the generator.

5   19.   A system according to any of claims 15 to 18 and operable in at least a tissue desiccation mode and a tissue cutting or vaporisation mode, wherein the generator includes a mode selection control, and wherein the control stage is operable automatically to adjust the radio frequency power supplied to the electrode structure to limit the peak generator output voltage to a first value
10   when the desiccation mode is selected and to at least one second value when the cutting or vaporisation mode is selected, the second value or values being higher than the first value.

20.   A system according to claim 18, wherein the first and second values are in the
15   ranges of from 150V to 200V and from 250V to 600V respectively, the voltages being peak voltages.

21.   A system according to any of claims 15 to 18, operable in at least a tissue desiccation mode and a tissue cutting or vaporisation mode and having a radio
20   frequency oscillator for driving the power device, wherein the generator includes a mode selection control coupled to the oscillator for adjusting the oscillator frequency of the oscillator so as to be higher than the resonant frequency of the series resonant output circuit in the cutting or vaporisation mode and lower than the said resonant frequency in the desiccation mode.

25
22.   A generator according to claim 14 and claim 7, wherein the values of the coupling capacitance and the components of the series-resonant circuit are such that the difference between the oscillator frequency and the resonant frequency is between $\frac{1}{4}(C_c f_r/C_r)$ and $(C_c f_r/C_r)$, where C_c is the coupling capacitance, C_r is
30   the capacitance element of the series-resonant circuit and f_r is the resonant frequency.

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23.   An electrosurgical generator for supplying radio frequency power to an
        electrosurgical instrument, the generator comprising a radio frequency output
        stage having at least a pair of electrosurgical output connections for the
        delivery of radio frequency power to the instrument, a radio frequency
5   oscillator for feeding a radio frequency signal to the output stage, and control
        circuitry including sensing means for deriving a sensing signal representative
        of the radio frequency signal delivered from the output connections, wherein
        the output stage comprises a series-resonant output circuit coupled to the output
        connections, the resonant frequency of the series-resonant output circuit being
10   different from the operation frequency of the oscillator, and wherein the control
        circuitry provides a feedback signal for controlling the delivered radio
        frequency power.

24.   A generator according to claim 23, wherein the output stage is a push-pull
15   output stage, and the control circuitry is operable to alter the on-time of one or
        more semiconductor devices forming part of the output stage independently of
        the frequency of operation.

25.   A generator according to claim 23 or claim 24, wherein the sensing means is
20   arranged to derive a sensing signal representative of the radio frequency peak
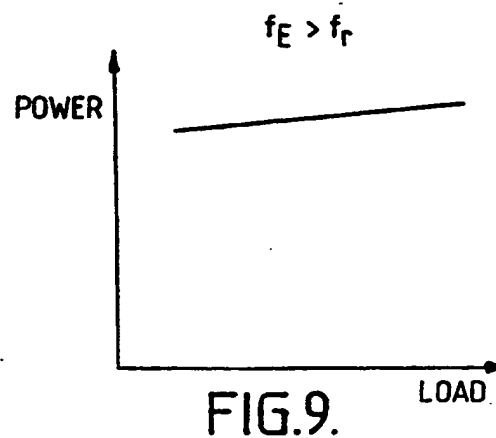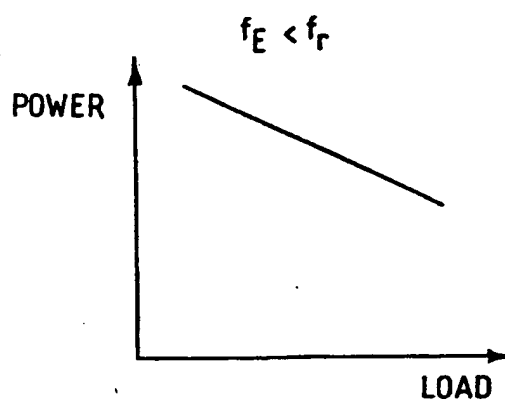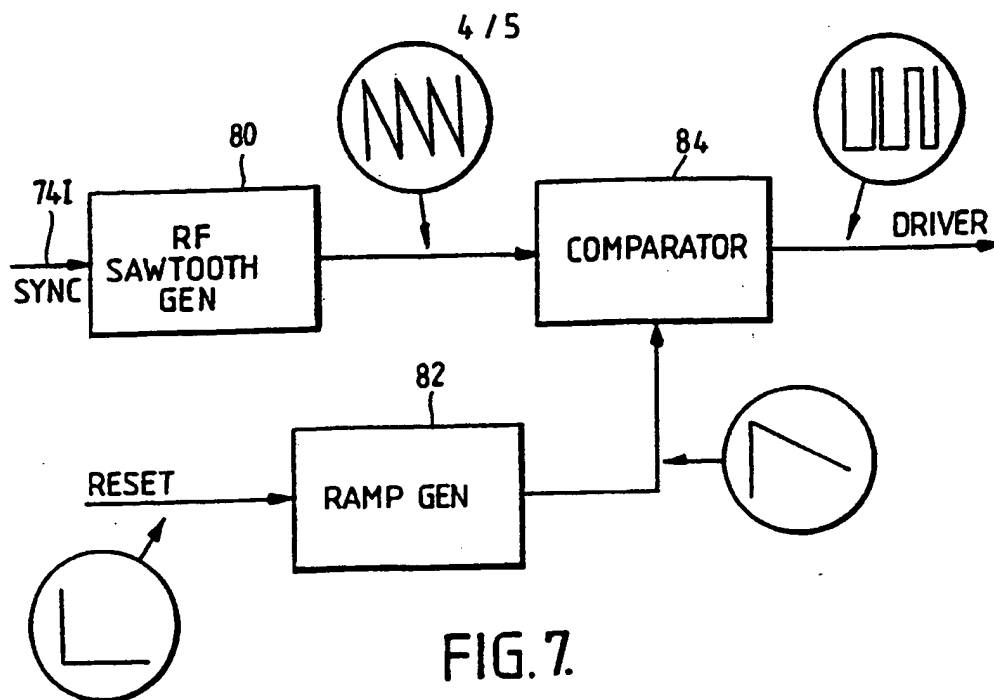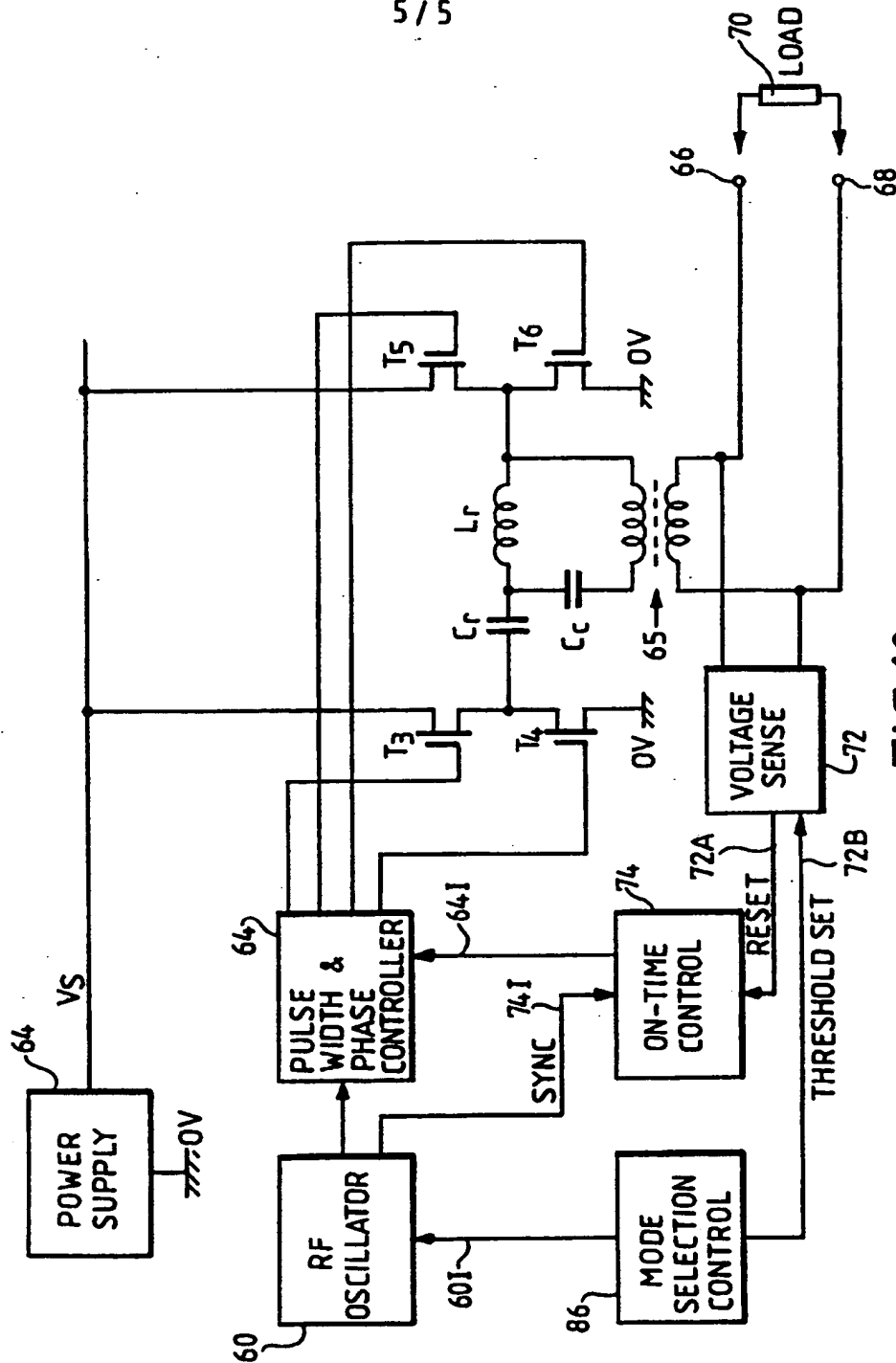   output voltage developed across the output connections.

FIG.1.

FIG.2.

FIG.3.

FIG.4.

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FIG.5.

FIG.6.

FIG.7.

FIG.8.

FIG.9.

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FIG.10

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   A61B17/39

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	WO 93 13718 A (VALLEYLAB) 22 July 1993 see abstract; figure 1	1,15,23

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
6 April 1998	16/04/1998

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INTERNATIONAL SEARCH REPORT

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